PB83-189068

Calculated Contribution of Surface Microlayer PCB to Contamination of Lake Michigan Lake Trout

Manhattan Coll.
Bronx, NY

Prepared for

Environmental Research Lab.-Duluth, MN

1982

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completi...

1. REPORT NO.	2.	3.
EPA-600/J-82-299	JOURNAL ARTICLE	PB83-169068

4. TITLE AND SUBTITLE	5. REPORT DATE
Calculated Contribution of Surface Microlayer PCB to Contamination of Lake Michigan Lake Trout	1982
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
Connolly, J. P., and R. V. Thomann	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
Environmental Engineering and Science Program Manhattan College Bronx, New York 10471	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
U.S. Environmental Protection Agency Environmental Research Laboratory-Duluth 6201 Congdon Boulevard Duluth, Minnesota 55804	14. SPONSORING AGENCY CODE EPA/600/03

15. SUPPLEMENTARY NOTES

J. Great Lakes Res. 8(2): 367-375 (1982)

16. ABSTRACT

The possible significance of PCB concentration in the surface microlayer of Lake Michigan to contamination of lake trout was examined using a modification of a previously developed food chain model. Vertically migrating zooplankton were assumed to spend a fraction of each day exposed to a surface microlayer with dissolved and phytoplankton PCB concentrations at values that resulted in an average exposure concentration 2.1 times greater than subsurface levels. Considering a worst case scenario, the model indicated that approximately 12% (3 µg/g) of the PCB concentration in adult lake trout could be contributed from the microlayer.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	10
	20. SECURITY CLASS *(This page)*	22. PRICE
	UNCLASSIFIED	

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

EPA-600/J-82-299
JOURNAL ARTICLE

J. Great Lakes Res. 8(2): 367-375
Internat. Assoc. Great Lakes Res. 1982

CALCULATED CONTRIBUTION OF SURFACE MICROLAYER PCB TO CONTAMINATION OF LAKE MICHIGAN LAKE TROUT

John P. Connolly and Robert V. Thomann
Environmental Engineering and Science Program
Manhattan College
Bronx, New York 10471

ABSTRACT. *The possible significance of PCB concentration in the surface microlayer of Lake Michigan to contamination of lake trout was examined using a modification of a previously developed food chain model. Vertically migrating zooplankton were assumed to spend a fraction of each day exposed to a surface microlayer with dissolved and phytoplankton PCB concentrations at values that resulted in an average exposure concentration 2.1 times greater than subsurface levels. Considering a worst case scenario, the model indicated that approximately 12% (3 μg/g)* of the PCB concentration in adult lake trout could be contributed from the microlayer.

INTRODUCTION

Organic and inorganic material is concentrated at the air-water interface of natural water systems in a few hundred micron thick region termed the surface microlayer. The extent of enrichment in this layer relative to subsurface water is a function of its physical and chemical properties as well as atmospheric deposition. Microlayers high in organic matter, such as surface slicks and windrows, exhibit the greatest enrichment. A summary of available data (Table 1) indicates that PCB enrichment in windrows is in the range of 30–1,000 compared to a range of 3–20 in unorganized surface layers.

The surface microlayer may have an important role in contamination of the aquatic food chain. The high concentrations of toxicants in the layer may contribute significantly to the body burden of zooplankton that migrate daily from subsurface waters to surface waters. In addition, atmospheric inputs may cause the microlayer to be less responsive than subsurface water to a reduction in point source toxicant loading, and consequently could slow the decline in body burden resultant from such reduction.

It is the purpose of this paper to estimate the possible contribution of the surface microlayer to observed PCB concentrations in Lake Michigan lake trout. A mathematical model of the bioenergetics and toxicant dynamics of a pelagic food chain is used to provide this estimate.

MODEL STRUCTURE

Computations were performed using a food chain model previously calibrated to the Lake Michigan pelagic food chain structure shown in Figure 1a (Thomann and Connolly 1982). This model calculates toxicant concentration in relation to age of each species and time considering uptake from food and water and loss through excretion and growth.

Each species is separated into discrete age classes. For each age class an initial weight and growth rate are specified, based on observed weight-age distributions. From this information, weight is computed in relation to time within an age class. Respiration is then calculated from weight-respiration relationships. Finally, food ingestion rate is computed as the intake necessary to produce the observed weight change given the metabolic requirement (respiration) and food assimilation efficiency. From this bioenergetic information, the dynamics of the toxicant, PCB, are computed.

The uptake of PCB from food is the product of a PCB assimilation efficiency, the food ingestion rate, and the concentration of PCB in the food. Uptake from water is computed assuming a diffusive transport mechanism analogous to oxygen uptake. The uptake rate is the product of the diffusivity of PCB relative to oxygen and the respiration rate normalized by the dissolved oxygen concentration. The excretion rate is simply the product of a rate constant and the concentration of

TABLE 1. PCB enrichment in the surface microlayer.

Environment	Concentration Surface Layer ng/L	Concentration Subsurface Water ng/L	Enrichment	Site Type	Ref.
Naragansett Bay, R.I.	4,200	150	28	Heavy Frothy Slick	1
	450	<50	>9	Unorganized Surface Layer	
Sargasso Sea (8 sites)	3.8–11.2	<0.9–3.6	3–>21	Unorganized Surface Layer	2
	42.6	<0.9	>47	Windrow	
Lake Michigan	—	—	6–7	Unorganized Surface Layer	3
Lake Mendota, Wi.	—	—	10^2–10^3	Windrow (Foam)	4

[1]Duce *et al.* (1972)
[2]Bidleman and Olney (1974)
[3]Rice *et al.* (1981)
[4]Eisenreich *et al* (1978).

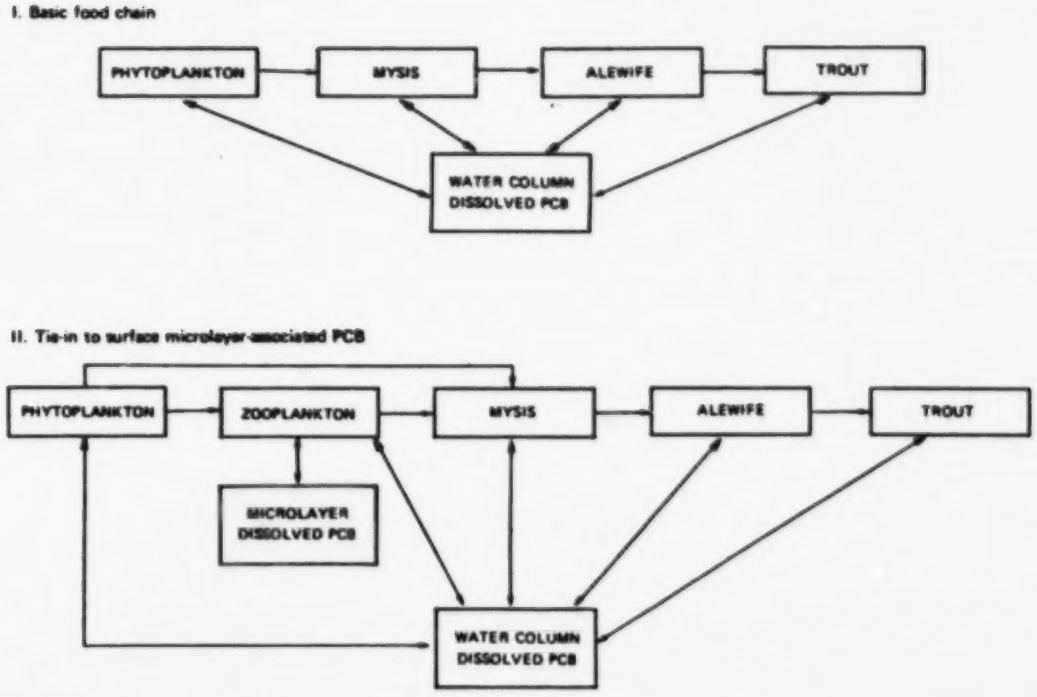

FIG. 1. Food chain structures used for Lake Michigan (I) basic pelagic food chain. (II) exposure to surface microlayer through zooplankton.

PCB within the species. The total mass balance equation is:

$$\frac{d\nu_i}{dt} = K_{ui}c + \sum_{j=1}^{n} \alpha_{i,j} C_{i,j}\nu_j - K'_i\nu_i \qquad (1)$$

where $K'_i = K_i + (dw_i/dt)/w_i$
K_i = excretion rate of organism i (d^{-1})
w_i = weight of organism i (g)
t = time (d)
K_{ui} = uptake rate of organism i (L/d-g)
$\alpha_{i,j}$ = chemical assimilation efficiency of organism i on organism j
$C_{i,j}$ = consumption rate of organism i on organism j (g prey/g pred.-d)
ν_i = concentration of chemical in a given organism of age class i (μg/g)
c = dissolved chemical concentration
n = total number of organisms (or age classes) preyed on by organism i

A more detailed description of the model structure is presented by Thomann and Connolly (1982).

To estimate the significance of the surface microlayer to contamination of predators (lake trout) in Lake Michigan, a modification of the original food chain structure was examined. This modification consisted of a zooplankton compartment inserted in series between *Mysis* and phytoplankton (Figure 1b). This compartment is assumed to be representative of migrating species that spend a portion of each day exposed to the microlayer.

ESTIMATION OF PARAMETERS

To calibrate the model it is necessary to determine the bioenergetic parameters associated with growth and respiration of each species, its assimilation and excretion rate of PCB, and the appropriate feeding structure. The parameter values for *Mysis*, alewife, and lake trout are presented by Thomann and Connolly (1982). A summary of these parameters including those presented below for zooplankton is given by Table 2.

Growth rate and life span of zooplankton are highly variable among species and under seasonal conditions. Temperature is an important controlling variable. For example, longevity of *Daphnia magna* averaged 108, 88, 42, and 26 days at 8, 10, 18 and 28°C, respectively (MacArthur and Baille 1929, as cited in Wetzel 1975). In the model, zooplankton life span was set at 100 days and divided into two 50-day age classes. Growth rate was assumed to be 0.028/day based on an initial dry weight of 0.6 μg and an adult dry weight of 10 μg.

The relationship between zooplankton wet weight, w(g), and respiration, R(g/g/d), was the same as the experimentally determined relationship for *Mysis* (Lasenby and Langford 1972):

$$R = 0.015W^{0.25} \qquad (2)$$

which is consistent with the general relationship found to hold for all poikilotherms (Schmidt-Nielson 1970).

Zooplankton food assimilation efficiency is a function of food type and rate of food ingestion. A summary of zooplankton food assimilation efficiency presented by Wetzel (1975) indicates a range of approximately 10 to 50%. A value of 30% was used in the model.

Ingestion rates at a prey concentration in the order of the average-annual phytoplankton concentration in Lake Michigan have been reported for

TABLE 2. Parameter values used in model.

	Zooplankton	Mysis	Alewife	Lake Trout
Growth Rate* (d^{-1})	0.028	0.019–0.0056	0.00245–0.00047	0.0058–0.0012
Respiration Rate** (g/g/d)				
$R = \alpha w^{\gamma}$ α	0.015	0.015	0.047	0.03
γ	-0.25	-0.25	-0.20	-0.295
Food Assimilation Efficiency	0.3	0.3	0.8	0.8
PCB Assimilation Efficiency	0.2	0.35	0.7	0.8
Ratio of uptake rate from water to excretion rate (L/g_d)	100	100	100	100

*growth rate decreases with age. Values shown are for first and last age class.
**lake trout respiration includes a swimming component not shown here.

the marine copepod *Calanus helgolandicus* (Paffenhofer 1971). At a temperature of 15°C and a phytoplankton concentration of 36 μg C/L, measured ingestion rates for 1 μg dry and 14 μg dry animals were 1.5 and 0.7 g/g/d, respectively. These values compare favorably with the 1.06 and 0.55 g/g/d computed from the growth rate, respiration rate, and assimilation efficiency presented above. Calculated ingestion rates for the zooplankton weight range used in the model vary from 1.29 and 0.69 g/g/d.

The zooplankton compartment in the model is assumed to represent the average individual on an annual time scale. Seasonal dynamics of growth and PCB uptake are not considered. This has the effect of removing oscillations of zooplankton PCB concentration that may exist in the field. The significance of such oscillations to the food chain is a topic that can be addressed only through a model that examines population dynamics.

The zooplankton were assumed to prey entirely on phytoplankton that are in equilibrium with water column PCB at a bioconcentration factor of 10^5 ($\mu g/g_{dry} \div \mu g/g_{water}$). This value of the bioconcentration factor has been shown to be typical of most aquatic species (Thomann 1981). Zooplankton were exposed to the microlayer for a fraction of each day during which time they were exposed to an elevated PCB concentration and consumed phytoplankton in equilibrium with this concentration. This equilibrium was computed using the bioconcentration factor equal to that of the water column. It is recognized that the microlayer is a heterogeneous mixture of organics and particulates that may result in a more non-polar environment: as such, the actual bioconcentration factor for the solute and phytoplankton in the microlayer may be different. However, the daily average PCB concentration to which zooplankton are exposed (water+ food) is fixed by the maximum PCB transfer from zooplankton to the lake trout that is consistent with observed lake trout PCB concentrations. Therefore, the simple assumption for the bioconcentration factor does not affect the final result but alters the extent of zooplankton exposure to the microlayer.

The daily average PCB concentration that the zooplankton are exposed to, c_e, depends on the fraction of each day spent in the microlayer, t_m, and the PCB concentration in the microlayer, c_m, relative to the concentration in subsurface water, c_w, i.e., the enrichment factor, F. The relationship may be written as:

$$c_e = c_w[1 + t_m(F - 1)] \quad (3)$$

The ratio of the daily average exposure concentration to the subsurface water concentration is the apparent daily enrichment factor, F_d:

$$F_d = 1 + t_m(F - 1) \quad (4)$$

Uncertainty associated with t_m and F preclude an accurate assessment of F_d. However, the fit of the model to observed PCB concentrations is a criterion for estimating the maximum value of F_d. A value of 2.1 was chosen.

The assimilation efficiency of ingested PCB was set at 0.2. Excretion rate was calculated to maintain a ratio of uptake rate from water to excretion rate consistent with a bioconcentration factor from water of 10^5. The rate decreased from 0.096/d to 0.048/d as zooplankton weight increased from 0.6 μg to 10 μg. Reported excretion rate of DDT by the adult marine copepod *Calanus finmarchicus* is 0.048/d (Harding and Vass 1977).

The interaction between zooplankton and *Mysis* in Lake Michigan is unclear. A qualitative examination of gut contents of Lake Michigan *Mysis* by McWilliam (1970) indicated that *Mysis* fed largely on phytoplankton, although some cladocerans and copepods were noted. Grossnickle (1978) found that June–August fecal pellets of Lake Michigan *Mysis* were commonly packed with diatoms and only an occasional zooplankton fragment. However, he did find that in laboratory experiments adult *Mysis* fed freely on both phytoplankton and zooplankton and concluded that adult *Mysis* may be predacious during periods of low phytoplankton concentration. In the model, adult *Mysis* had a 90%–10% consumption split between phytoplankton and zooplankton.

RESULTS AND DISCUSSION

Surface Microlayer Contribution

Given the zooplankton bioenergetic information, calibration of the model to PCB data was controlled by the values assigned to the zooplankton PCB assimilation efficiency, the enrichment factor for the microlayer and the time spent in the microlayer. Adjustments during calibration were restricted to reported ranges. Information on assimilation efficiency of PCB by zooplankton is not available, and the value of 0.2 used was based on the values used for the other levels in the food chain model.

Assuming a subsurface dissolved PCB concentration of 5 ng/L, the calculated PCB concentrations for alewife and lake trout are consistent with 1971 observed concentrations (Figure 2). Although the values are higher than those computed without a zooplankton group and microlayer exposure (Thomann and Connolly 1982) they are, in general, within a standard deviation of the mean observed concentrations. The average concentration in each level of the food, with and without microlayer exposure, is shown in Figure 3.

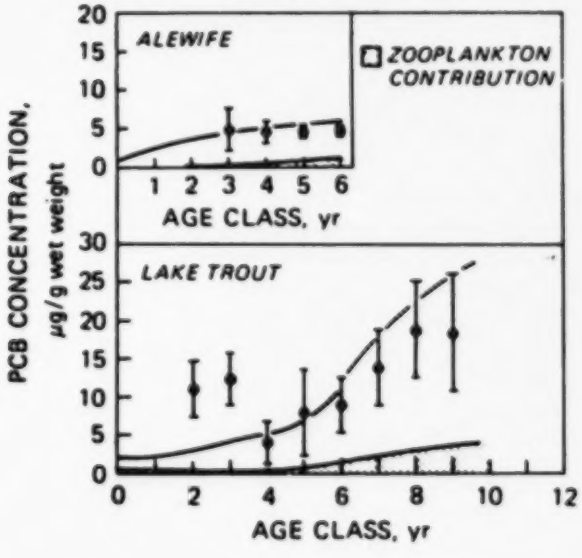

FIG. 2. Comparison of 1971 observed PCB concentrations in alewife and lake trout with food chain model calculation. Dotted area shows contribution of surface microlayer through zooplankton to computed PCB concentrations in alewife and lake trout.

The contributions of the microlayer to PCB concentrations in alewife and lake trout are shown as the dotted areas in Figure 2. These contributions were calculated by setting the water concentration to zero so that the transfer of PCB through the food chain results only from the exposure to the microlayer. Approximately 14% of the computed PCB in adult alewife and 12% of the computed PCB in adult trout result directly from zooplankton exposure to the microlayer. The maximum concentration of the 9-year-old lake trout due just to the microlayer is about 3 µg/g on a whole body basis.

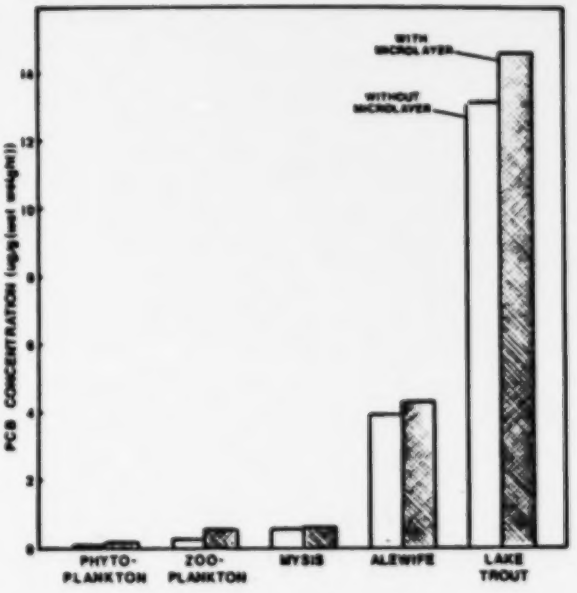

FIG. 3. Average PCB concentration in each level of the food chain with and without zooplankton exposure to the microlayer. Phytoplankton concentration with microlayer is the average concentration to which zooplankton are exposed. Other food chain levels are exposed to the phytoplankton without microlayer at all times.

Assuming the basic structure of the model to be valid, 12% or 3 µg/g is the maximum contribution that the microlayer could have made to the lake trout since any additional PCB would result in failure to reproduce the observed concentrations. Therefore, it is a conservative estimate. A more accurate assessment of the surface microlayer contribution cannot be made because of uncertainty in the enrichment factor and time spent in the microlayer.

A given microlayer contribution can be calculated with a range of values for enrichment factor and time in the microlayer, as indicated by Equation 4. For the 12% microlayer contribution to lake trout the observed range of PCB enrichment factors in unorganized surface layers (3–20) corresponds to time in the microlayer ranging from 13 to 1.4 hours per day (Figure 4). At a windrow enrichment factor of 1,000, a daily exposure of only 1.5 minutes results in the 12% contribution. Parameter ranges for microlayer contributions below the assumed maximum are also shown in Figure 4.

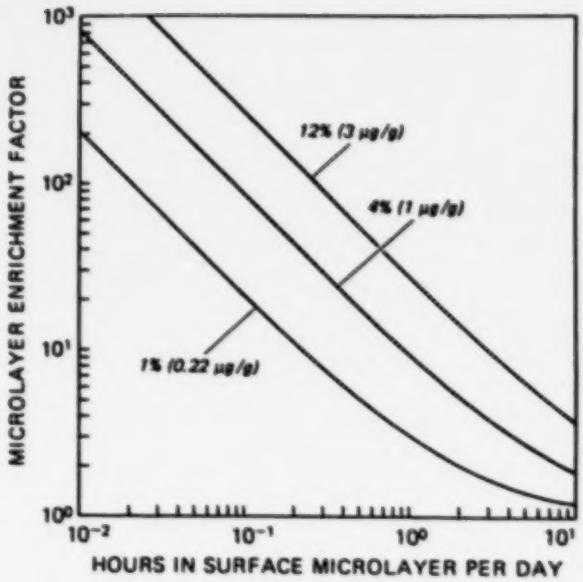

FIG. 4. Combinations of microlayer enrichment factor and time spent in the microlayer that yield surface microlayer contributions to 9-year-old lake trout PCB concentrations of 1%, 4%, and 12%. Numbers in parentheses are the actual concentrations due to surface microlayer.

Influence of Microlayer on Effectiveness of Load Reductions

The PCB enrichment in the surface microlayer results from atmospheric deposition and chemical and physical characteristics that cause a partitioning of PCB between the microlayer and subsurface water. A significant question is the response of this layer to reduction in point source loadings to Lake Michigan. Because atmospheric deposition is a direct input to the microlayer, whereas point source loadings are direct inputs to the subsurface water, a reduction in point source loadings without a reduction in atmospheric loading would have a greater impact on the subsurface water than on the microlayer. The microlayer could then become more significant as a potential source of contamination to the food chain.

To quantify the microlayer response to point source load reductions an idealized system that consists of microlayer and subsurface water compartments is considered. While it is recognized that in the lake a dynamic interaction exists in which microlayers are continually formed and destroyed, the two-compartment idealization provides useful insight into the relative behavior of surface and subsurface regions.

The general equations that result from applying the principle of conservation of mass to the particulate (adsorbed) PCB, c_{p_m}, and dissolved PCB, c_{d_m}, in the microlayer are:

$$V_m \frac{dc_{p_m}}{dt} = W_{a_p} + E'_p(c_{p_w} - c_{p_m}) + K_o c_{d_m} m - K_1 c_{p_m} \quad (5)$$

$$V_m \frac{dc_{d_m}}{dt} = W_{a_d} + E'_d(c_{d_w} - c_{d_m}) - K_o c_{d_m} m + K_1 c_{p_m} \quad (6)$$

where V_m is the volume of the microlayer, c_{p_w} and c_{d_w} are the concentrations of particulate and dissolved PCB in the subsurface water, respectively, W_{a_p} and W_{a_d} are the atmospheric loadings of particulate and dissolved PCB, respectively, K_0 and K_1 are the adsorption and desorption rates of PCB, respectively, m is the concentration of adsorbing solids, E'_p is the bulk dispersion coefficient of particulate PCB and E'_d is the bulk dispersion coefficient of dissolved PCB.

Assuming temporal steady-state and that the total PCB concentration, c, is the sum of the particulate and dissolved components, Equations 5 and 6 may be summed to yield:

$$0 = W_a + E'_p(f_{p_w}c_w - f_{p_m}c_m) + E'_d(f_{d_w}c_w - f_{d_m}c_m) \quad (7)$$

where W_a is the total atmospheric load, f_p is the fraction of total PCB that is particulate, f_d is the fraction of total PCB that is dissolved, and the subscripts w and m indicate the subsurface water and the surface microlayer, respectively.

An analogous development for the water column (subsurface water) yields:

$$0 = W_p + E'_p(f_{p_m}c_m - f_{p_w}c_w) + E'_d(f_{d_m}c_m - f_{d_w}c_w) - Qc_w - wAf_{p_w}c_w \quad (8)$$

where W_p is the point source loading, Q is the flow through the lake, w is the settling velocity of the adsorbing solids, and A is the surface area for settling. Combining Equations 7 and 8 the concentration of PCB in the water column may be expressed as:

$$c_w = \frac{W_T}{Q + wAf_{p_w}} \quad (9)$$

where W_T is the sum of the point source and atmospheric loadings.

Equation 7 may be solved for the microlayer enrichment factor, yielding:

$$F = \frac{c_m}{c_w} = \frac{W_a}{(E'_p f_{p_m} + E'_d f_{d_m})c_w} + \beta \qquad (10)$$

where

$$\beta = \frac{E'_p f_{p_w} + E'_d f_{d_w}}{E'_p f_{p_m} + E'_d f_{d_m}}$$

Substituting Equation 9 into Equation 10:

$$F = \frac{Q + wAf_{p_m}}{E'_p f_{p_m} + E'_d f_{d_m}} \left(\frac{W_a}{W_T}\right) + \beta$$

The enrichment factor is thus dependent on the atmospheric load relative to the total load, the rate of PCB transport out of the water column (flow plus settling) relative to the mixing between the water column and microlayer, and, β, the distribution and rates of mixing of particulate and dissolved PCB.

The fraction of PCB that is particulate has been observed to be approximately 0.6 in the surface microlayer of Lake Michigan (Rice *et al.* 1981) and has been calculated to be approximately 0.1 in the subsurface waters (Thomann and Di Toro 1981). Using these values, β is calculated to range from 2.24 to 0.167 as the ratio of particulate to dissolved PCB dispersion varies from 0 to ∞. If the dispersions are equal β is 1. Given the magnitude of the observed enrichment factors, this possible variation of β is not significant and the parameters controlling the enrichment factor are the loadings and the ratio of PCB transport out of the water column to the mixing between the water column and microlayer.

The response of the microlayer to a reduction in point source PCB loadings may be calculated from Equation 11 or, if an independent estimate of the water column response is available, from Equation 10. An analysis of the Lake Michigan water column response to point source loading reductions (Thomann and Di Toro 1982) indicates that elimination of point source loadings may decrease water column PCB to as low as 2 ng/L. This represents a 60% decrease of the 5 ng/L concentration used in the model calibration.

To calculate the corresponding decrease in microlayer PCB, Equation 10 is rewritten as

$$c_m = \alpha + \beta c_w \qquad (12)$$

where

$$\alpha = \frac{W_a}{E'_p f_{p_m} + E'_d f_{d_m}}$$

and then substituted into the equation for the percentage decrease, R, in microlayer PCB:

$$R = \left(\frac{c_{m_1} - c_{m_2}}{c_{m_1}}\right) \times 100 \qquad (13)$$

to yield

$$R = \beta \left(\frac{c_{w_1} - c_{w_2}}{c_{m_1}}\right) \times 100$$

This equation may be re-expressed as

$$R = \beta \left(\frac{1 - c_{w_2}/c_{w_1}}{F_1}\right) \times 100 \qquad (14)$$

The subscripts 1 and 2 denote the original and reduced conditions, respectively.

Considering the range of 3–20 for enrichment factor in unorganized surface layers, and assuming β is 1, the range of concentration reduction in the surface microlayer corresponding to the 60% reduction in the subsurface water is 20–3%. For the maximum enrichment factor in windrows of 1,000, the microlayer reduction is 0.06%. The relationship between the reduction of subsurface PCB and the reduction in microlayer PCB for various initial enrichment factors is shown in Figure 5. Note that for enrichment factors greater than 50, decreases in subsurface PCB concentrations due to point source loading reductions have little effect on microlayer PCB.

The difference in the response of the microlayer and the water column to point source load reduction is controlled by the rate of mass transport between the microlayer and the subsurface water relative to mass transport out of the water column and the atmospheric loading to the microlayer, as indicated by Equation 11.

Considering the limiting case of no microlayer response, 3 μg/g of lake trout PCB would be con-

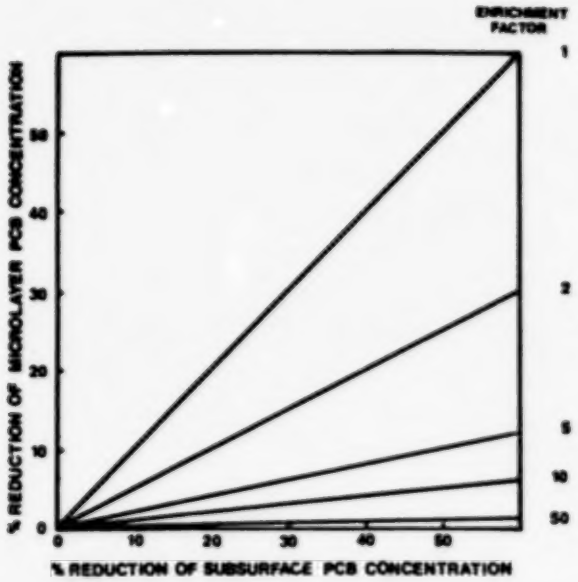

FIG. 5. Calculated percent reduction in microlayer PCB concentration in relation to the percent reduction in subsurface water PCB concentration resulting from a reduction in point source loadings for various microlayer enrichment factors.

tributed by the microlayer regardless of water column PCB concentrations. At the water column PCB concentration representative of atmospheric load only (2 ng/L), the projected PCB concentration in adult lake trout without microlayer exposure is approximately 10 μg/g (Thomann and Connolly 1981). Zooplankton exposure to the microlayer would then increase that estimate to a maximum of 13 μg/g. The significance of the microlayer increases from a 12% contribution to a 23% contribution.

Thomann and Connolly (1982) indicate that without microlayer exposure 2 ng/l may be sufficiently low to decrease PCB concentrations in the edible portion of the lake trout below the FDA action limit. However, the microlayer contribution may keep these concentrations near or even above the limit.

CONCLUSIONS

The surface microlayer may be a significant source of PCB contamination to the food chain of Lake Michigan. Vertical migration of zooplankton into the microlayer where they are exposed to elevated PCB concentrations in both food (phytoplankton and detritus) and water and subsequent consumption of these zooplankton by higher levels of the food chain provides a mechanism of toxicant transfer to the top predators.

The microlayer may provide sufficient contamination to keep PCB levels in adult lake trout near the FDA action limit. It is possible that the combined contributions of the microlayer and sediment (through benthic communities) may keep concentrations above the FDA limit even after water column concentrations have declined to near zero. This possibility is currently being tested through inclusion of *Pontporeia affinis*, a benthic invertebrate, in the food chain model.

The extent of enrichment of the microlayer and the percentage of time zooplankton spend in the microlayer are critical parameters controlling the transfer of microlayer associated toxicant to the top predators. Uncertainty of their magnitudes allows only an analysis of the worst case possible contribution of microlayer PCB to the food chain. Both parameters should be the subject of future research to provide further insight as to the importance of the microlayer to food chain contamination.

ACKNOWLEDGMENTS

This work was carried out as part of a cooperative agreement (R805916010) with the USEPA-Large Lakes Laboratory at Grosse Ile, Michigan. The support of Project Officer William Richardson of the laboratory is gratefully acknowledged. In addition, the assistance of Janice Rollwagen of Manhattan College in the data reduction and computer program execution greatly benefited this research.

REFERENCES

Bidelman, T. F., and Olney, C. E. 1974. Chlorinated hydrocarbons in the Sargasso Sea atmosphere and surface water. *Science* 183:516–518.

Duce, R. A., Quinn, J. Q., Olney, C. E., Piotrowicz, S. R., Ray, B. J., and Wade, T. L. 1972. Enrichment of heavy metals and organic compounds in the surface microlayer of Narragansett Bay, Rhode Island. *Science* 176:161–163.

Eisenreich, S. J., Elzerman, S. J., and Armstrong, D. E. 1978. Enrichment of micronutrients, heavy metals, and chlorinated hydrocarbons in wind-generated lake foam. *Environ. Sci. Technol.* 12(4):413–417.

Grossnickle, N. E. 1978. The herbivorous and predaceous habits of *Mysis relicta* in Lake Michigan. Ph.D. Thesis, The University of Wisconsin—Madison.

Harding, G. C. H., and Vass, W. P. 1977. Uptake from sea water and clearance of ^{14}C-p,p'-DDT by the marine copepod *Calanus finmarchicus*. *J. Fish. Res. Board Can.* 34:177–182.

Lasenby, D. C., and Langford, R. R. 1972. Growth, life history and respiration of *Mysis Relicta* in an Arctic and temperate lake. *J. Fish. Res. Board Can.* 29:1701– 1708.

McWilliam, P. S. 1970. Seasonal changes in abundance and reproduction in the opossum shrimp, *Mysis relicta* Loven, in Lake Michigan. M.S. Thesis, University of Sidney, Australia.

Paffenhofer, G. A. 1971. Grazing and ingestion rates of nauplii, copepodids and adults of the marine planktonic copepod *Calanus helaplandicus*. *Marine Biology* 11:286–298.

Rice, C. P., Erstfeld, K. M., and Eadie, B. J. 1981. The role of surface films in the transfer of organic pollutants at the air/water interface, presented at the Twenty-Fourth Conference on Great Lakes Research, Columbus, Ohio, Apr. 28–30.

Schmidt-Neilsen, K. 1970. Energy metabolism, body size and problems of scaling. *Federation Proceedings* 29(4):1524–1532.

Thomann, R. V. 1981. Equilibrium model of fate of microcontaminants in diverse aquatic food chains. *Can. J. Fish. Aquat. Sci.* 38:280–296.

_____, and Connolly, J. P. 1982. An age dependent model of PCB in the Lake Michigan food chain. In preparation.

_____, and Di Toro, D. M. 1982. Preliminary model of the fate of toxic substances in the Great Lakes. Submitted for publication, *J. Great Lakes Res.*

Wetzel, R. G. 1975. *Limnology*. W. B. Saunders Co., Philadelphia, Pa.